



Technology Area Roadmap for In Space Propulsion Technologies

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"We're all pilgrims on the same journey - but some pilgrims have better road maps."

- Nelson DeMille








Technology Area Overview

- For both human and robotic exploration, traversing the solar system is a struggle against time and distance.
- ***Advanced In-Space Propulsion technologies will enable much more effective exploration of our Solar System.***
 - Mission designers will be able to plan missions to "fly anytime, anywhere and complete a host of science objectives at the destinations" with greater reliability and safety.
- With a wide range of possible missions and candidate propulsion technologies with very diverse characteristics, the question of which technologies are "best" for future missions is a difficult one.
 - A portfolio of technologies should be developed so as to allow optimum propulsion solutions for a diverse set of missions and destinations.
- Once Earth orbit is achieved, high thrust is no longer required. Low thrust technologies can be used if they can be operated for long durations.
 - Several advanced in-space propulsion technologies offer performance that is significantly better than that achievable with state-of-the-art chemical propulsion.

This roadmap describes the portfolio of in-space propulsion technologies that can meet future space science and exploration needs.



Benefits

- Development of technologies within this TA will result in technical solutions with improvements in thrust levels, specific impulse, power, specific mass (or specific power), volume, system mass, system complexity, operational complexity, commonality with other spacecraft systems, manufacturability and durability.
- These types of improvements will
 -  Yield decreased transit times
 -  Increased payload mass
 -  Decreased costs
 -  Enable missions to new science/exploration targets
 -  Provide potential propulsion breakthroughs that will revolutionize space exploration.

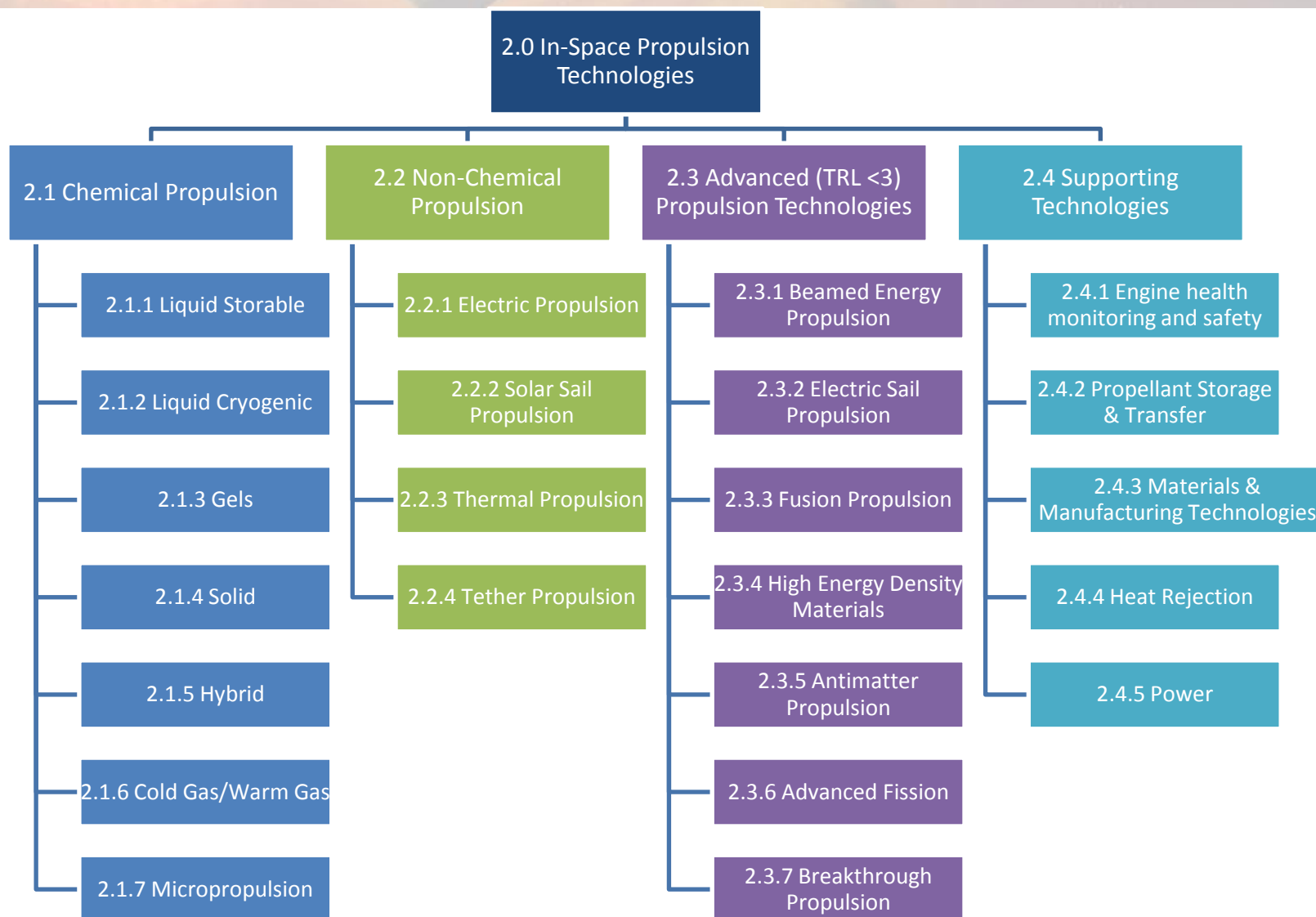


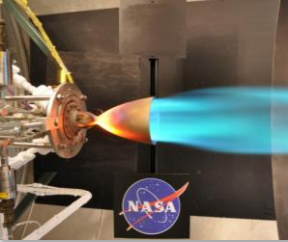
Traceability to NASA Strategic Goals

- The In-Space Propulsion Roadmap team used the NASA strategic goals and missions detailed in the following reference materials in the development of the roadmap:
 - Human Exploration Framework Team products to extract reference missions with dates
 - SMD Decadal Surveys
 - Past Design Reference Missions, Design Reference Architectures, and historical mission studies
 - In-Space Propulsion Technology Program concept studies
 - Internal ISS utilization studies.



Technology Area Breakdown Structure





2.1 Chemical Propulsion

- Chemical Propulsion involves chemical reaction of propellants to move or control spacecraft.
 - Example technologies include:
 - **Liquids** - rocket systems using mono/bipropellants, high energy oxidizers, cryogenics (LO₂/LH₂ & LO₂/CH₄) as propellant.
 - **Gels** - fuels that are thixotropic (shear-thinning) that provide higher density, reduced sloshing, and leak resistance.
 - **Solids** - fuels that premix oxidizer and fuel and are typically cast formed.
 - **Hybrids** - technology that combines benefits of solids and liquids.
 - **Cold/Warm Gas** - uses expansion of inert cold/warm gas to generate thrust.
 - **Micropropulsion** - subset of above technologies (solids, gas, monopropellants) applied to small/microsatellite applications.
- Applications include primary propulsion, reaction control, station keeping, precision pointing, and orbital maneuvering.
- Technology Development in this area will result in improvements in thrust levels, volume, system mass, system complexity, operational complexity, and commonality with other spacecraft systems.



Example Data

Chemical Propulsion Technologies

2.1.2.2 LO ₂ , LH ₂	TECHNICAL CHALLENGES	MILESTONES TO TRL 6
<p>SOA is MMH/NTO at TRL 9 for Reaction Control Systems (RCS) and orbital maneuvering propulsion, which are integrated. Development of LOX/LH₂ RCS (liquid propellants) allows integration with an upper stage that uses LOX/LH₂. An O₂/H₂ RCS typically involves taking low-pressure propellants from the main tanks, pumping to higher pressure, turning liquid to a gas, and then storing in a gas accumulator. The TRL is 4-5 with engines having been tested, dating back to 1970 for early shuttle designs before MMH/NTO was selected based on the complexity, dry mass, and volume of O₂/H₂ Orbital Maneuvering System (OMS)/RCS.</p>	<p>The challenge is the complexity and dry mass of taking low pressure propellant from the tanks, pumping to higher pressure, turning liquid to a gas, and then storing in a gas accumulator. O₂/H₂ RCS engines have been built and successfully tested. The other feed system components (pumps, heat exchangers, accumulators) are more critical issues. Cryogenic fluid management issues must also be addressed.</p>	<p>Develop components (pumps, heat exchangers, accumulators) for the O₂/H₂ feed system and perform integrated system level tests.</p>
2.1.3 Gelled & Metalized-Gelled Propellants		
<p>Gelled and metallized fuels are a class of thixotropic (shear thinning) fuels which improved the performance of rocket and airbreathing systems in several ways: increased rocket specific impulse, increased fuel density, reduced spill radius in an accidental spill, lower volatility during low pressure accidental propellant fires, reduced fuel sloshing, and lower leak potential from damaged fuel tanks (due to higher propellant viscosity). Military systems have sought gelled fuels for all of these reasons. NASA systems have studied gelled fuels analytically and experimentally for lunar and Mars missions, upper stages, interplanetary robotic missions, and launch vehicle applications. Increased fuel density and increased engine specific impulse are the primary benefits. Missile flight tests, 1999, 2001, with earth-storable propellants: Inhibited Red Fuming Nitric Acid for the oxidizer, and gelled-MMH/Carbon for the fuel.</p>	<p>Gelled cryogenic propellants have only been tested in laboratory experiments and have not yet flown in a space representative environment. One potential issue to be addressed would be boil-off and a corresponding shift in gellant-loading in the fuel. Cryogenic fluid management issues must also be addressed. Storable NTO/MMH/Aluminum, Oxygen/RP-1/Aluminum, and Cryogenic Oxygen/Hydrogen/Aluminum are the primary candidates to be investigated. The primary challenges are with gelling the fuels with the aluminum particles.</p>	<p>Recapture gelled hydrogen/cryogenic fuel work from 1970's. Cryogenic fluid management issues must also be addressed. Large scale (500-1000 lbs thrust) RP-1/Aluminum, and Hydrogen/Aluminum engine and component testing must be conducted.</p>



2.2 Non-chemical Propulsion

- Non-Chemical Propulsion serves same set of functions as chemical propulsion, but without using chemical reactants.
 - Example technologies include:
 - **Electric Propulsion** - systems that accelerate reaction mass electrostatically and/or electromagnetically.
 - **Solar or Nuclear Thermal Propulsion** - systems that energize propellant thermally.
 - **Solar Sail and Tether Propulsion** - systems that interact with the space environment to obtain thrust electromagnetically.
- Similar to Chemical, applications include primary propulsion, reaction control, station keeping, precision pointing, and orbital maneuvering.
- Technology Development in this area will result in improvements in thrust levels, specific impulse, power, specific mass (or specific power), and system mass.

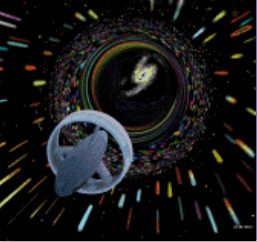




Example Data

Non-Chemical Propulsion Technologies

2.2.1.1.2 Arcjets	TECHNICAL CHALLENGES	MILESTONES TO TRL 6
Arcjets use an electric arc to heat the propellant prior to expansion through a nozzle. Additional heat may be added chemically, with hydrazine propellant for example. Arcjets are a mature (TRL 9) technology with hundreds of thrusters in operation on commercial communications satellites, primarily for station keeping. Off-the shelf hydrazine arcjet systems have power levels of 1670 to 2000 W. Lower power hydrazine arcjets (~500 W) have achieved TRL 5-6. Ammonia arcjets at 30 kW were flight-qualified (TRL 7). Laboratory model hydrogen arcjets have power levels ranging from 1 to 100 kW, but did not progress beyond ~TRL 4.	Minor product improvements are being made on existing products, but there is little mission pull for more advanced arcjets.	No immediate applications that require advanced arcjets.
2.2.1.2 Electrostatic		
2.2.1.2.1 Ion Thrusters		
Ion thrusters employ a variety of plasma generation techniques to ionize a large fraction of the propellant. High voltage grids then extract the ions from the plasma and electrostatically accelerate them to high velocity at voltages up to and exceeding 10 kV. Ion thrusters feature the highest efficiency (60 to >80%) and very high specific impulse (2000 to over 10,000 sec) compared to other thruster types. Over 130 ion thrusters have flown in space on over 30 spacecraft in both primary propulsion and satellite station keeping applications. The propellant presently used is xenon for its high atomic mass, easy storage on spacecraft and lack of contamination issues, although other propellants can be used. Flight thrusters operate at power levels from 100 W to 4.5 kW. Various ion thrusters are at TRL 9 (13cm XIPS, 25cm XIPS, NSTAR, T5 Kaufman Thruster, RIT10, 10 ECR, and ETS-8). The 7.2 kW NEXT ion thruster is already at TRL6 and requires flight demonstration or mission application.	Ion thruster performance and life is determined by the grids. Thrusters operate at voltages of 750 V - 10,000 V, and voltage breakdown of closely spaced multi-aperture grids is an important issue. Improvements in low-erosion grid materials and longer life cathodes are needed for future deep space missions. Improvements in efficiency based on better plasma generator design is needed. Improved modeling & model-based design & life predictions are also needed for future ion thruster development.	Various ion thrusters are at TRL 9 (13cm XIPS, 25cm XIPS, NSTAR, T5 Kaufman Thruster, RIT10, 10 ECR, and ETS-8). The next generation GRC thruster, NEXT is already at TRL6 and requires flight demonstration or mission application. Next larger ion thruster is 25 kW JPL NEXIS thruster, which is at TRL5 and requires only thermal environmental testing and life qualification to achieve TRL6.
2.2.1.2.2 Hall Thrusters		
Hall thrusters are electrostatic thrusters that utilize a cross-field discharge described by the Hall effect to generate the plasma. An electric field perpendicular to the applied mag-netic field accelerates ions to high exhaust velocities, while the transverse magnetic field inhibits electron motion that would tend to short out the electric field. Hall thruster efficiency and specific impulse is somewhat less than that achievable in ion thrusters, but the thrust at a given power is higher and the device is much simpler. Over 240 xenon Hall thrusters have flown in space since 1971 with a 100% success rate. Commercially developed flight Hall thrusters operate between 0.2 and 4.5 kW with 50% efficiency, thrust densities of 1 mN/cm ² , and Isp of 1200-2000 secs. Hall thrusters have been demonstrated from 0.1 to 100 kW with efficiencies of 50-70%. Recent research has demonstrated operation with alternative propellants and Isp increases to 3000-8000 secs.	Scaling to high-power and achieving sufficient lifetime are central challenges. Scaling to higher power (>10 kW) normally results in increased specific mass (kg/kW), but provides longer lifetime due to greater amounts of wall material inherent in larger designs. A major challenge is to capitalize on recent breakthroughs on reducing wall erosion rates to realize very long life and throughput (>1000 kg) and increase Isp. Life validation of high-power, long-life thrusters requires development of physics-based models of the plasma & erosion processes.	Hall thruster power level must progress from thrusters capable of 10's of kW of power to systems of multiple thrusters capable of the order of 1 MW. Key milestones for high power Hall thrusters are demonstration of long-life technology on large thrusters (10's to 100's of kW), development of 100 kW or multi-100kW thrusters with demonstration of performance and life, and development of associated power processing units (PPU's). The 10-20-kW class thrusters developed by AFRL must be leveraged to achieve TRL6 within 3-5 years as a stepping stone to higher power thrusters. Larger thrusters operating at power levels of 50 kW and higher require performance demonstration at Isp from 2000 to 3000 sec, environmental testing and life qualification to achieve TRL6.



2.3 Advanced Propulsion (<TRL3)

- Advanced Propulsion Technologies use chemical or non-chemical physics to produce thrust, but are lower technical maturity (TRL < 3) than those described in 2.1 and 2.2.
 - Example technologies include:
 - **Beamed Energy** - systems that use beamed laser or RF energy from ground source to heat propellant to generate thrust (e.g. lightcraft)
 - **Electric Sail** - system that uses a number of long/thin high voltage wires to interact with solar wind to generate thrust.
 - **Fusion** - systems that use fusion reactions indirectly (fusion power system to drive EP), or directly (fusion reaction provides kinetic energy to reactants used as propellant)
 - **High Energy Density Materials** - materials with extremely high energy densities to greatly increase propellant density and potential energy.
 - **Antimatter** – system that converts large percentage of fuel mass into propulsive energy through annihilation of particle-antiparticle pairs.
 - **Advanced Fission** – enhanced propulsion ideas that utilize fission reactions to provide heat to propellants (and in some cases utilize magnetic nozzles)
 - **Breakthrough Propulsion** – area of fundamental scientific research that seeks to explore and develop deeper understanding of nature of space-time, gravitation, inertial frames, quantum vacuum, and other fundamental physical phenomenon with objective of developing advanced propulsion applications.
- Predominant applications are in the area of primary propulsion, but some areas may also be applicable to reaction control, station keeping, precision pointing, and orbital maneuvering.
- Technology Development in this area will result in improvements in thrust levels, specific impulse, power, specific mass (or specific power), volume, system mass.





Example Data

Advanced (TRL < 3) Propulsion Technologies

2.3 Advanced (TRL <3) Propulsion Technologies

Description and State of the Art

Technical Challenges

TRL Maturation

2.3.1 Beamed Energy Propulsion

Beamed energy propulsion uses laser or microwave energy from a ground or space based energy source and beams it to an orbital vehicle which uses it to heat a propellant, with the advantage being high exit velocity of exhaust products over traditional chemical propulsion. Earth-to-Orbit laser propulsion technology has been investigated both analytically and experimentally as a first step to orbital transfer. In space applications to be demonstrated are orbit transfer and earth escape. Other in-space applications could be to de-orbit orbital debris by way of ablation.

Development of MW Free Electron Lasers.
Development of novel optics/tracking and pointing systems for orbit transfers.
Propellant feeds or ablative propellants will also need to be technically addressed.
Development of efficient capture and transformation of beamed energy into propulsive energy (e.g., heat exchangers, direct plasma breakdown in propellant).

Demonstrate thermal rocket mode using liquid, gaseous, or Delrin ablation propellant for in space maneuvers.



Example Data

Advanced (TRL < 3) Propulsion Technologies (cont'd)

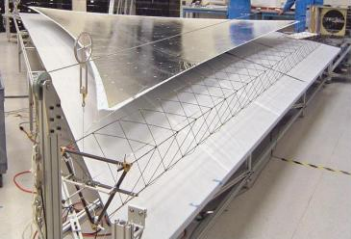
2.3.2 Electric Sail Propulsion	Technical Challenges	TRL Maturation
<p>Consists of a number of thin, long, and conducting wires that are kept in a high positive potential by an onboard electron gun. The positively charged wires repel solar wind protons, thus deflecting their paths and extracting momentum from them. Simultaneously they also attract electrons from the solar wind plasma. A way to deploy the wires is to rotate the spacecraft and have the centrifugal force keep them stretched. By fine-tuning the electrical potentials of individual wires and thus the solar wind force individually, the attitude of the spacecraft can also be controlled. Deployment of multikilometer length wires in space has been demonstrated (see electrodynamic tether propulsion). Electron guns have also been flown in space. Other technical approaches to achieve electrostatic propulsion from the solar wind include the superconducting magsail and Mini-Magnetospheric Plasma Propulsion (M2P2), but none of these have yet been demonstrated; all propulsive effects have been only predicted in theory and modeling.</p>	<p>Quantification of thrust magnitudes with on-orbit data.</p> <p>Demonstration of noninterfering centrifugal deployment of multiple wires from a single spacecraft.</p> <p>Validation of current collection and electrostatic propulsion from the solar wind.</p> <p>Validation of electrostatic attitude control in the solar wind.</p>	<p>Validate physics models.</p> <p>Develop system level performance models.</p> <p>Develop control laws for attitude control using multiple wire anodes.</p> <p>Perform subscale space flight validation (outside of the magnetosphere).</p>
2.3.3 Fusion Propulsion		
<p>Fusion propulsion involves using fusion reactions to produce the energy required for the spacecraft propulsion. This can be accomplished either indirectly (with a fusion reactor producing electrical power that is in turn utilized in an electric thruster), or directly, by using the thermal/kinetic energy resulting from the fusion reactions to accelerate a propellant. This is accomplished either by creating a hot, thermal plasma that is then expelled through a magnetic nozzle to provide thrust (in the same manner as in a plasma thrusters) or using high-energy, charged particle, fusion products to create the hot, thermal plasma in the thrust chamber. The physics and related technologies are still under investigation at the laboratory scale level. A gain (energy out of the reaction to energy into the reaction) of approximately 1 has been achieved, but for useful fusion propulsion, a gain of 100 to 1000 is needed.</p>	<p>Creation of a sustained fusion reaction that can drive a plasma thruster with a specific mass low enough ($\alpha < 4$) to be competitive with advanced fission is the primary challenge. Production of a positive energy output with Deuterium-Tritium reactions has yet to be demonstrated even in ground-based Tokamak reactor concepts.</p> <p>Production of a thermal plasma suitable for an electric thruster from high-energy fusion products (such as would come from an aneutronic fusion reactor) is needed.</p>	<p>Develop plasma thruster concept capable of efficiently converting high-energy, charged particle fusion products into propellant energy.</p> <p>Demonstrate plasma thruster concept on the ground in space-like simulated environment.</p> <p>Perform testing and validation of engine technology.</p>



Example Data

Advanced (TRL < 3) Propulsion Technologies (cont'd)

2.3.7 Breakthrough Propulsion	Technical Challenges	TRL Maturation
Breakthrough Propulsion Physics is specifically looking for propulsion breakthroughs from physics. It is not looking for further technological refinements of existing methods. It is an area of fundamental scientific research that seeks to explore and develop a deeper understanding of the nature of space-time, gravitation, inertial frames, quantum vacuum, and other fundamental physical phenomenon with the pinnacle objective of developing advanced propulsion applications and systems that will revolutionize how we explore space. Past research efforts have yielded a number of publications in peer-reviewed literature detailing applied theoretical models and laboratory investigation results/conclusions.	Fundamental scientific re-search in this area is a high risk/high payoff venture. In-dividual investigations may yield good science, but not always result in a propulsion physics break-through. Chal-lenges in this area are to de-velop theoretical mod-els and high fidelity laboratory ex-periments for model verification/validation (cou-pling of gravity & electromag-netism, vacuum fluctuation energy, warp drives & worm-holes, & superluminal quantum effects). Because these propul-sion goals are presumably far from fruition, a small sus-tained investment is needed to identify & support afford-able, near-term, & credible research that will make incre-mental progress toward these propulsion goals.	Progress in this area will be accomplished by prioritizing and pursuing focused research to: 1) establish if an idea has propulsion applications, 2) investigate if the effect of interest can be observed in the laboratory, 3) begin engineering breadboard development to produce the desired effect in a manner useful for spaceflight applications. Once a concept has progressed through these wickets, it should be ready to migrate beyond the TRL 3 level and could be recategorized as a gamechanging technology.



2.4 Supporting Technologies

- Supporting Technologies support some in-space propulsion system or subsystem, but are described in more detail in other OCT Technology Area Roadmaps.
 - Example crossover areas include:
 - Engine Health Monitoring & Safety
 - Propellant Storage & Transfer
 - Materials and Manufacturing Technologies
 - Heat Rejection
 - Power
- Technology Development in this area will result in improvements in power, specific mass (or specific power), system mass, system complexity, operational complexity, and manufacturability/durability.





Interdependency with Other TA

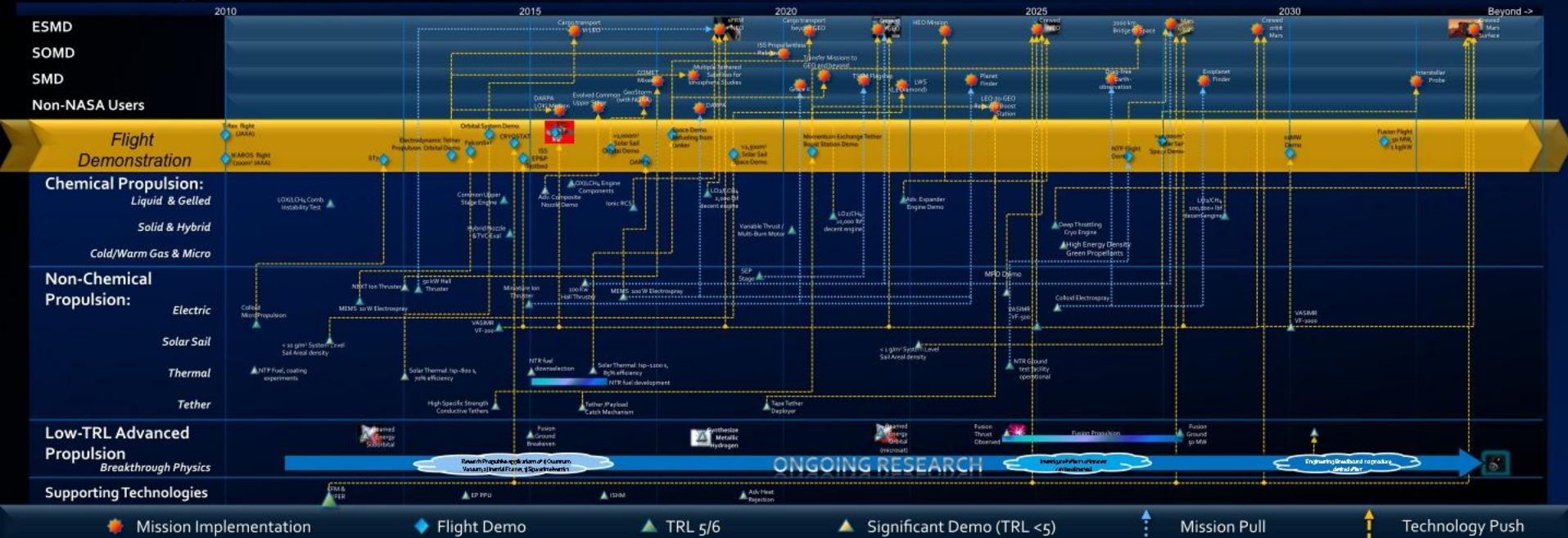
	LAUNCH PROPULSION SYSTEMS	SPACE POWER AND ENERGY STORAGE SYSTEMS	ROBOTICS, TELE-ROBOTICS, AND AUTONOMOUS SYSTEMS	COMMUNICATION AND NAVIGATION SYSTEMS	HUMAN HEALTH, LIFE SUPPORT AND HABITATION SYSTEMS	HUMAN EXPLORATION AND SCIENTIFIC INSTRUMENTS, OBSERVATORIES, AND SENSOR SYSTEMS	ENTRY, DESCENT, AND LANDING SYSTEMS	NANOTECHNOLOGY	MODELING, SIMULATION, INFORMATION TECH. AND PROCESSING	MATERIALS, STRUCTURAL AND MECH. SYSTEMS, AND MANUFACTURING	GROUND AND LAUNCH PROCESSING	THERMAL MANAGEMENT SYSTEMS	AERONAUTICS			
	TA1	TA2	TA4	TA5	TA6	TA7	TA8	TA9	TA10	TA11	TA12	TA13	TA14	TA15		
Relationship with TA2: In-Space Propulsion	S	F	F					T	S		F	T	F			
		Extensive			S	Close synergy in tasks										
		Limited			T	Technologies from TA2 to related TA										
					F	Technologies from related TA to TA2										

- Interdependencies were identified with several other Technology Area road maps
 - The relationships were categorized as synergistic with technologies in another TA (S), dependent on technologies in another TA (F-from), or supporting technologies in another TA (T-to)

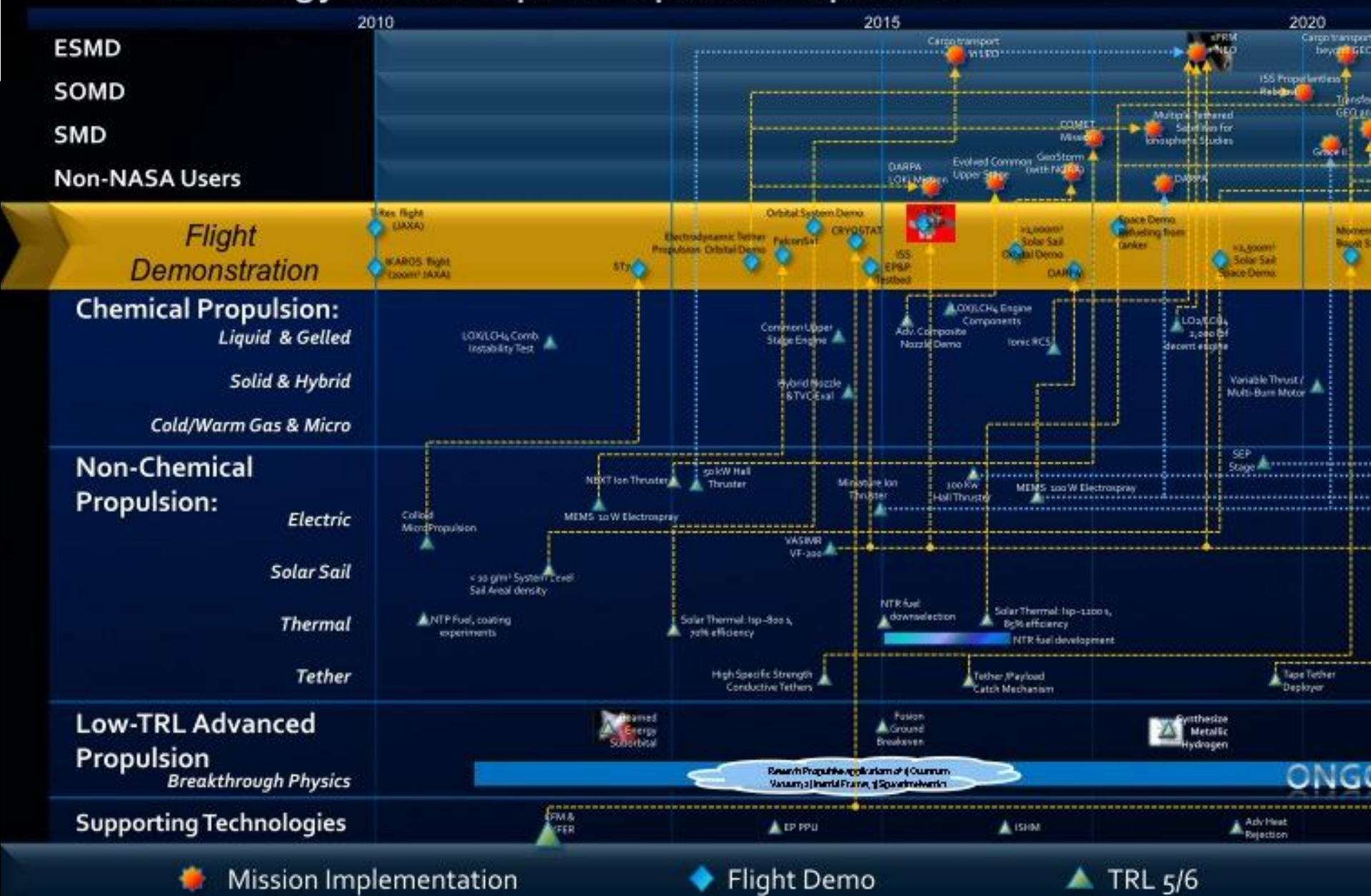


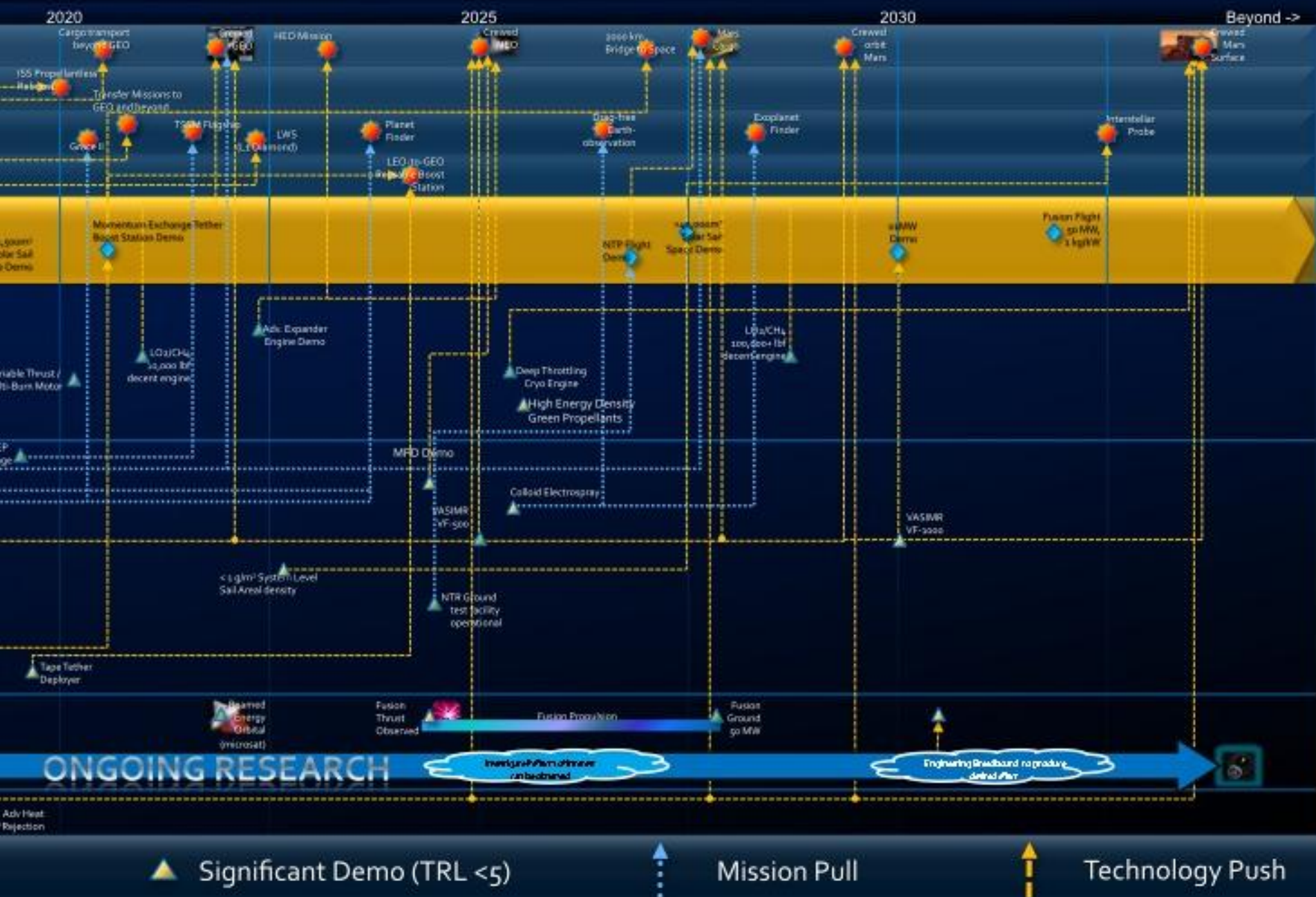
TA02 TASR

Technology Roadmap: In Space Propulsion



Technology Roadmap: In Space Propulsion







Top Technical Challenges

Rank	Description	Time
1	Power Processing Units (PPUs) for ion, Hall, and other electric propulsion systems	N
2	Long-term in-space cryogenic propellant storage and transfer	M
3	High power (e.g. 50-300 kW) class Solar Electric Propulsion scalable to MW-class Nuclear Electric Systems	M
4	Advanced in-space cryogenic engines and supporting components	M
5	Developing and demonstrating MEMS-fabricated micropropulsion thrusters	N
6	Demonstrating large (over 1000 m ²) solar sail equipped vehicle on-orbit	N
7	Nuclear Thermal Propulsion (NTP) components and systems	F
8	Advanced, high performance, space storable propellants	M
9	Long-life (>1 year) electrodynamic tether propulsion system in LEO	N
10	Advanced In-Space Propulsion Technologies (TRL <3) to enable a robust technology portfolio for future missions.	F

N – near (present to 2016), M – mid (2017-2022), F – far (2023-2028)

(Timeframe for maturation to TRL 6)



Benefits to Other National Needs

- More capable and efficient in-space propulsion will benefit NASA, national defense, and the commercial space industry – virtually any organization that builds or uses space satellites. Specific technologies with multi-user applicability include:
 - Metalized Gelled Propellants for higher performance and safer missile systems
 - Long-Duration Cryogenic Propulsion for high-energy orbit transfer
 - Electric Propulsion for longer-life communications and Earth observing satellites
 - Solar Sails for sustained observation of the Earth's polar regions (NOAA)
 - Research toward Nuclear Thermal Propulsion will lead to smaller and more efficient reactor designs (DOE)
 - Tethers will enable lower-cost access to space and orbit transfer
 - Development of new technologies from robust research and technology development will enable new missions and applications for all potential users.



Summary

- This roadmap describes a portfolio of in-space propulsion technologies that can meet future space science and exploration needs.
 - Balances the need for technologies supporting both human and robotic exploration
 - Offer a diverse set of approaches to achieve new in-space propulsion capabilities across several promising technologies operating on very different physics
 - Identifies specific high-priority technologies with investment need in the near-, mid- and far-term.